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Work accomplished and published between March 1979 and March 1980 involving the high-frequency excess noise and flicker noise in GaAs MESFETs, the high-frequency excess noise and flicker noise in MOSFETs, noise in triodelike JFETs, and noise in two MOSFET types made by the DMOS process is reviewed.

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FINAL REPORT

"A STUDY OF FLICKER NOISE IN MOSFETS"

ARMY RESEARCH OFFICE GRANT DAAG29-80-C-0078

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FOR THE PERIOD MARCH 1979 - MARCH 1980

1. Review of work accomplished and published between March 1979 and March 1980

Work by Takagi, carried out the previous year, was published during the period. It involved work on the high-frequency excess noise and flicker noise in GaAs MESFETs (1), the high-frequency excess noise and flicker noise in MOSFETs (2), noise in triode-like JFETs (3), and noise in two MOSFET types made by the DMOS process (4).

The excess noise effect in GaAs MESFETs probably involves hot electron noise, since it becomes more pronounced at lower temperatures, whereas the flicker noise is not fully understood (1). The nature of the excess noise in MOSFETs is not fully understood, it is probably not of the hot-electron type; the flicker noise in the same devices agrees roughly with the low-frequency noise measurements on the same devices (2). Theory and experiments were given for the triode-like JFETs (3); the results agree qualitatively with what we know about ordinary JFETs. DMOS devices are devices in which an n^+-source and a narrow p-region are diffused in simultaneously; they were built on an n^- or a p^- substrate, respectively, so that the structures were n^+-p-p^--n^+ and n^+-p-n^--n^+, respectively. From the differences in noise behavior of the two types it was concluded that the p-region gave $1/f^{0.6}$ noise, the p^--region gave 1/f noise, whereas the n^--region gave no noticable noise contribution (4).

It was attempted to demonstrate that the 1/f noise behavior of highly doped semiconductors (5) and the 1/f noise in electrolytic resistors and concentration cells (6), that were previously

interpreted as mobility fluctuation noise, can also be explained as number fluctuation noise.

Two subsequent surveys were given of the oxide trap model of 1/f noise in MOSFETs operated at low drain bias (7,10). In the first survey an error in the elementary theory of MOSFET modeling (8) was not corrected for, but the error was corrected in the second version. It is then possible to express the drain noise spectrum in terms of an effective trap density at the Fermi level, $[N_T(E_f)]_{eff}$.

The error just mentioned comes about because the elementary theory does not take into account the slow increase of the turn-on voltage V_T with increasing gate bias V_g nor the slow decrease in the mobility μ with increasing gate bias V_g. As a consequence the spectrum of the equivalent gate noise emf is off by a factor $I_d^2/[g_m^2(V_g-V_T)^2]$, which lies between 2 and 20 for different devices and at different gate bias. This factor follows from the expression

$$g_m(V_g-V_T)/I_d = 1 - dV_T/dV_g + (d\mu/dV_g)(V_g-V_T)/\mu,$$

where g_m is the transconductance and I_d the drain current. The error is due to the transformation from the drain noise spectrum $S_{I_d}(f)$ to the equivalent gate noise spectrum $S_{V_{eq}}(f)$ and is independent of any noise model.

A study was made of the noise in hydrogenated amorphous silicon resistors (9). The noise is resistance fluctuation noise, probably of the generation-recombination type, and the current flow is space charge limited. There was no 1/f noise to speak of.

It was shown that Vandamme's mobility fluctuation noise model for MOSFETs violates the Boltzmann transport equation and must therefore be modified (11). This work was performed under another grant but is of significance to this grant.

Flicker noise measurements in MOSFETs indicate that the effective oxide trap density at the Fermi level, $[N_T(E_f)]_{eff}$ has plausible values, so that the oxide trap model is a viable one. The measurements do not <u>prove</u>, however, that the model is correct (12).

Flicker noise measurements in a particular type of GaAs MESFET gives a transition from $1/f$ to $1/f^2$ around a frequency of a few thousand Hertz (13). Such a transition would be expected for the usually assumed distribution in time constants

$$g(\tau)d = \frac{d\tau/\tau}{\ln(\tau_1/\tau_o)} \qquad \text{for } \tau_o < \tau < \tau_1 \tag{1}$$

$$g(\tau)d\tau = 0 \text{ otherwise}$$

For such a distribution the transition occurs at $\omega\tau_o \simeq 1$.

2. <u>Review papers published during the period</u>

During the period two review papers were published.

The first dealt with space-charge-limited solid-state diodes (14) and reviewed much work, including noise work, done under previous ARO grants. The paper sums up their properties, including their noise behavior.

The second paper gave a review of flicker noise in electronic devices (15). It sums up the work done on this problem during

the last 30 years and gives an outlook on what can be expected in the field. Writing this review has stimulated our thinking and has shaped our 1/f noise program.

3. Theses completed and (or) defended during the period

Mr. S. K. Kim completed his Ph.D. thesis (16) and defended it in April 1980. The outstanding results, besides the work on amorphous silicon resistors already mentioned, were the demonstration of the presence of some hot electron noise in short-channel (4.2 μ meter) JFETs above 150°K, which was masked by donor generation-recombination noise below 150°K, and the presence of a considerable amount of hot electron noise in buried channel MOSFETs of 2.0 μ meter channel length. From the donor g-r noise an activation energy of 61 mV was deduced. At low fields this activation energy should be twice the ionization energy (44 mV) of the donors. The lower activation energy at high fields is due to the Poole-Frenkel effect and implies an average field of about 4000 V/cm in the channel.

Mr. Hak Song Park finished his M.S. thesis in September 1978 and defended it in April 1980 (17). It dealt with 1/f noise in silicon-on-sapphire MOSFETs and was performed under an RCA grant. We mention it here, since the results have a direct bearing on our program.

4. Outlook on future work

There are two rival theories of 1/f noise in semiconductors and semiconductor devices: the number fluctuations model and the mobility fluctuation model.

The first, dating back to the middle 1950's, was proposed by McWhorter (18) and explained the noise in terms of number fluctuation noise caused by the interaction, via tunneling, of the free carriers with traps in the surface oxide. Undoubtedly the theory held for the materials and devices manufactured in those days. But semiconductor technology has made great strides since these days, so that it is no longer certain that the model applies to modern materials and devices.

The second theory was proposed by Hooge (19). It says that the noise is mobility fluctuation noise. The exact cause is not specified, but it is merely assumed that the noise satisfies the relationship

$$\frac{S_\mu(f)}{\mu^2} = \frac{\alpha_H}{fN} \tag{2}$$

where N is the number of carriers, f the frequency and α_H is Hooge's parameter, which often has a value around 2×10^{-3}. With the help of Eq. (2) a number of data can then be explained.

There are several experiments that seem to <u>require</u> that mobility fluctuation noise is the predominant mechanism in several present-day materials and devices. The most convincing one is an experiment by Bosman and Zijlstra (20), which indicates that for space-charge-limited solid-state diodes the conductance fluctuation decreases rapidly with increasing field E at high fields as

$$\frac{S_g(f)}{g^2} = \frac{\alpha_H}{fN(1 + E/E_c')^2} \tag{3}$$

where E_c' is considerably smaller than the critical field strength

E_c occuring in the field-dependent mobility

$$\mu = \frac{\mu_o}{(1 + E/E_c)} \tag{4}$$

This seems to imply mobility fluctuation noise. For in the mobility fluctuation model one would indeed expect the noise to decrease with increasing field, whereas the number fluctuation noise should be independent of the field, so that the factor $(1 + E/E_c')^2$ should be missing in (3) for that model.

This now can lead to several ways of discriminating between the two noise models. We mention here a few possibilities:

1. Under the assumption that the noise is number fluctuation noise, the drain noise spectrum in MOSFETs at low drain bias is described by

$$S_{I_d}(f)/V_d^2 = (q^2\mu^2 w/L^2 f)[N_T(E_f)]_{eff}/\varepsilon \tag{5}$$

where w is the device width, L is length and ε is McWhorter's tunneling parameter. However, the mobility fluctuation noise model gives

$$S_{I_d}(f)/(I_d V_d) = \alpha_H q\mu/(fL^2) \tag{6}$$

It is thus possible to evaluate $[N_T(E_f)]_{eff}$ and α_H as functions of the gate bias V_g, since $\varepsilon \approx 10^8$ cm^{-1}. One finds that $[N_T(E_f)]_{eff}$ has reasonable values. The value of α_H lies between 10^{-5} and 10^{-4}, depending upon the device under study. This in and by itself does not discriminate between the two models. But in the case of silicon on sapphire MOSFETs, which are much

noisier, α_H is larger than 2×10^{-3}, which seems to suggest that they can better be explained by the number fluctuation model.

2. $S_{V_{eq}}(f)$ at low drain bias varies as the square of the oxide thickness t for the number fluctuation model, whereas it varies linearly with t for the mobility fluctuation model. This result is independent of the error $I_d^2/[g_m^2(V_g-V_T)^2]$ in $S_{V_{eq}}(f)$, since the error occurs equally in each model. Measurement of $S_{V_{eq}}(f)$ versus oxide thickness t can thus discriminate between both models.

3. $S_{I_d}(f)$ versus V_d for short-channel MOSFETs, obtained by letting V_d go from low values through saturation, behaves differently for the two models. The number fluctuation model gives that $S_{I_d}(f)$ increases monotonically with increasing drain bias reaching a maximum value at saturation. The mobility fluctuation model gives a maximum in $S_{I_d}(f)$ before saturation, reaching a lower value at saturation. Most devices seem to agree with the first model, but there are some devices that agree better with the second. We are now investigating under what conditions the latter situation seems to occur.

4. Since the data seem to indicate that α_H can be much smaller than the value 2×10^{-3} originally proposed, whereas the mobility fluctuation noise is strongly suppressed in the hot electron regime, we may now have an opportunity of explaining the value $\alpha_H < 2 \times 10^{-8}$, deduced from Hiatt's measurements on very short-channel JFETs at saturation (21) in terms of mobility fluctuation noise rather than in terms of the oxide trap model. We are looking into this possibility.

It is expected that these approaches will be further developed during the coming months and that the study will indicate under what condition each model applies. We may then also have an opportunity to pinpoint the physical model for the mobility fluctuation noise mechanism.

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